

## EVALUATION OF THE SPAR THERMAL ANALYZER ON THE CYBER-203 COMPUTER

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### CYBER 203

The purpose of this effort is to make the CYBER 203 (fig. 1) vector computer available for thermal calculation and assess the use of such a vector computer for thermal analysis. Strengths of the CYBER 203 include the ability to perform, in vector mode using a 64 bit word, 50 million floating point operations per second (MFLOPS) for addition and subtraction, 25 MFLOPS for multiplication and 12.5 MFLOPS for division. The speed of scalar operation is comparable to that of a CDC 7600 and is some 2 to 3 times faster than Langley's CYBER 175s. The CYBER 203 has 1,048,576 64-bit words of real memory with an 80 nanosecond (nsec) access time. Memory is bit addressable and provides single error correction, double error detection (SECDED) capability. The virtual memory capability handles data in either 512 or 65,536 word pages. The machine has 256 registers with a 40 nsec access time.

The weaknesses of the CYBER 203 include the amount of vector operation overhead and some data storage limitations. In vector operations there is a considerable amount of time before a single result is produced so that vector calculation speed is slower than scalar operation for short vectors. In some cases the vector length at which vector processing becomes faster than scalar may be as large as 70. Also, the terms of a vector must be stored in contiguous locations for vector operations--e.g. terms in a two dimensional array must be used by columns. This last limitation is partially offset by availability of fast routines to "gather" data from non-contiguous locations and store the data in contiguous locations using a vector of indices which indicate which terms are to be collected. Similarly, efficient routines are available for the inverse operation (scatter) and transposing a matrix.

## **CYBER 203**

### **STRENGTHS**

- **SPEED** - VECTOR OPERATION  $\approx 30$  MFLOPS ( $\pm$ ) (64 BIT)
  - SCALAR OPERATION  $\approx 7600 \approx 2$  TO  $3 * \text{CYBER 175}$
- **MEMORY** - 1024 K 64 BIT WORDS, 80 nsec ACCESS
  - SECCDED ERROR PROCESSING
- **VIRTUAL MEMORY ARCHITECTURE**
  - SMALL PAGES - 512 WORDS
  - LARGE PAGES - 65536 WORDS
- **LARGE REGISTER FILE** - 256 40 nsec REGISTERS

### **WEAKNESSES**

- VECTOR OPERATION OVERHEAD PENALIZES USE OF SHORT VECTORS
- VECTOR DATA MUST BE IN CONTIGUOUS LOCATIONS  
PARTIALLY OFFSET BY FAST TRANSPOSE, GATHER/SCATTER

Figure 1

## SPAR THERMAL ANALYZER

To provide a general in-house integrated thermal-structural analysis capability the Langley Research Center is having the SPAR Thermal Analyzer (fig. 2) developed under contract by Engineering Information Systems, Inc. The SPAR Thermal Analyzer is a system of finite-element processors for performing steady-state and transient thermal analyses. The processors communicate with each other through the SPAR random access data base. As each processor is executed, all pertinent source data is extracted from the data base and results are stored in the data base.

The tabular input (TAB), element definition (ELD) and arithmetic utility system (AUS) processors are used to describe the finite element model. The data base utility (DCU) processor operates on the data base. The plotting processors (PLTA, PLTB) provide the capability to plot the finite element model for model verification but do not directly plot temperatures. The thermal geometry (TGEO) processor performs geometry checking of the thermal elements and total model. The thermal processors for steady state analysis (SSTA) and transient analysis (TRTA, TRTB and TRTG) are described in References 1 and 2. In addition there are several processors not shown in the figure for extraction of thermal fluxes, system matrices and system operating characteristics.

On a scalar computer the processors may be executed interactively or in a batch mode. A typical analysis is usually performed as a sequence of interactive and batch operations where model development and verification is performed interactively and actual thermal calculations performed in batch mode. The program operates on UNIVAC, CDC, PRIME and VAX computers.

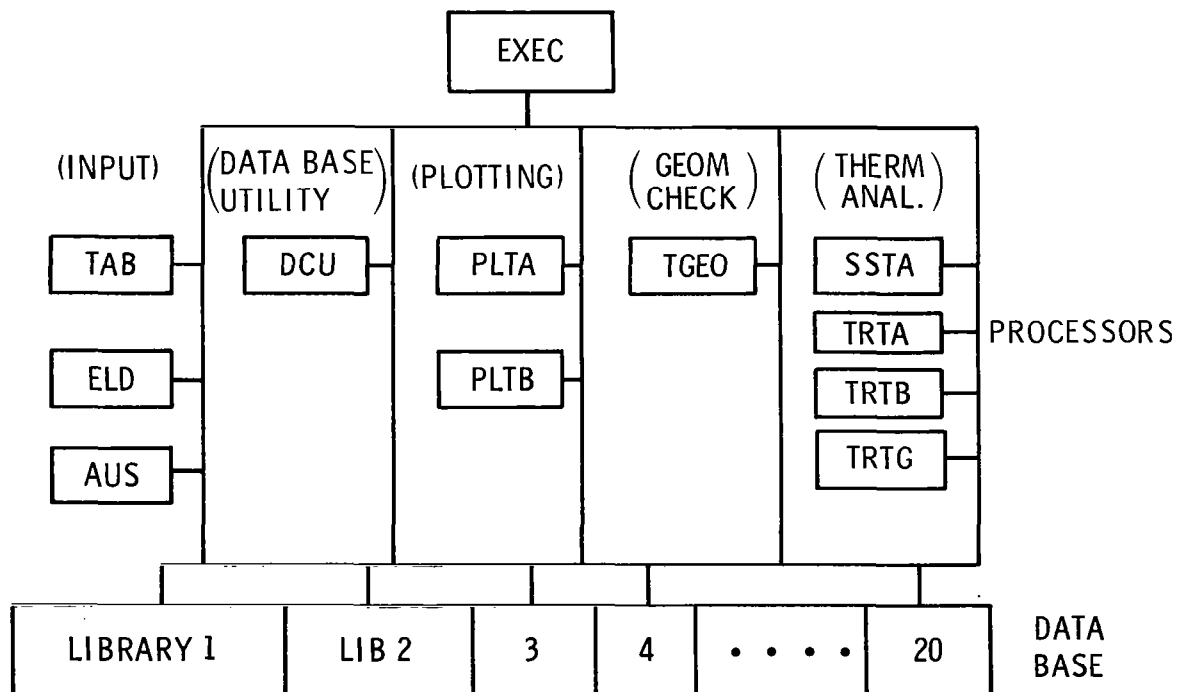


Figure 2

## SPAR THERMAL ANALYZER ON THE CYBER 203

The SPAR Thermal Analyzer shown in the last figure was modified to operate on the CYBER 203 in a scalar processing mode (fig. 3). A number of transient thermal analyses were performed with this scalar version to determine the CPU times required and ensure that the program produced correct results. The CPU times were used for comparison with the CYBER-175 and as a basis to evaluate future vectorization. A description of seven of the problems and their scalar mode solution times are presented in subsequent figures.

In addition, six short subroutines were modified so that vector operations could be performed when applicable. The modified subroutines were selected because of their heavy use in implicit solutions where longer vectors are used and the ease with which the modification could be made. No changes were made in the internal data ordering for vector processing. The effect of this simple approach to vectorization will be discussed later.

Several program modifications were required due to differences between the CYBER 203 and other CDC computers at Langley. The virtual memory capability makes it possible to load the complete program without overlaying. It also required changing some data initialization from DATA statements to executable statements since DATA statements are effective only the first time a program segment is placed in memory. The lack of random access to external files required the storage of the data base in dimensioned arrays during execution and the sequential transfer of these arrays to external files upon execution completion for restart capability.

In addition to the changes required by differences in machine architecture several compiler bugs required coding changes to make the program execute properly.

- CONVERSION EFFORT

- COMPLETE SCALAR OPERATION
  - VECTORIZE A FEW ROUTINES
  - HIGH USE, EASY VECTORIZATION

- CHANGES REQUIRED

- PARAMETER INITIALIZATION (VIRTUAL MEMORY)
  - INTERNAL DATA STRUCTURE (NO RANDOM ACCESS FILES)
  - RESTART CAPABILITY

- COMPILER PROBLEMS

Figure 3

COMPARISON OF THE CYBER 175 AND  
CYBER 203 CPU TIME FOR SPAR PROCESSORS

The results presented in figure 4 are discussed with the individual problem slides. In general, the only processor showing appreciable improvement is TRTB which requires the most effort in large problems, and the improvement is based on problem size and probably on the ratio of CPU to I/O effort. Processors that perform large amounts of data input and character manipulation are appreciably slower on the CYBER 203.

PROCESSOR PROBLEM	TAB	AUS	ELD	TGEO	TRTB	DCU	TOTAL
FRAME	0.40*	0.49	0.33	0.10	6.78	0.40	8.49
	0.96**	1.51	0.96	0.06	4.15	0.39	8.01
ANTENNA	0.24	1.89	0.49	0.14	43.03	0.61	46.41
	0.37	4.33	1.24	0.08	25.55	0.58	32.15
SINGLE BAY	0.25	1.23	0.29	0.10	85.22	1.12	88.21
	0.37	3.49	0.60	0.06	52.45	0.96	57.93
WING	1.87	1.38	3.18	0.59	126.90	10.72	144.64
	4.01	5.78	7.96	0.40	58.77	8.93	85.84
CYLINDER	0.85	0.15	0.99	0.16	156.60	4.30	164.48
	0.82	0.32	1.42	0.63	62.23	2.40	67.82
MULTIWALL	1.14	5.95	2.47	1.27	210.99	1.07	222.89
	1.81	21.91	7.11	0.56	116.31	0.95	148.66
THREE BAYS	1.64	4.97	1.33	1.38	365.23	1.40	375.95
	2.28	18.35	2.54	0.58	184.90	1.25	210.05

\* - CYBER 175    \*\* - CYBER 203 (SCALAR MODE)

Figure 4

## SPACE SHUTTLE FRAME

An aluminum space shuttle fuselage frame (Refs. 3 and 4) is shown in figure 5. The finite element model has 190 grid points, 158 thermal elements and is heated by time-dependent surface temperatures. Heat is transferred by conduction in the aluminum and insulation and radiation from the inner insulation surface. Implicit solution times on the CYBER 175 and 203 are shown at the bottom for a temperature history of 1000 seconds with a computational time interval (DT) of 10 seconds. Figure 4 shows the CPU time in seconds (CYBER 175 on upper line, CYBER 203 on lower line) for each of the processors used in the analyses. For the FRAME problem, which is relatively small, the savings in the actual transient analysis (TRTB) is largely offset by the poor relative performance of the CYBER 203 in the other processors where problem input requires a large amount of character manipulation.

## GALLEGOS

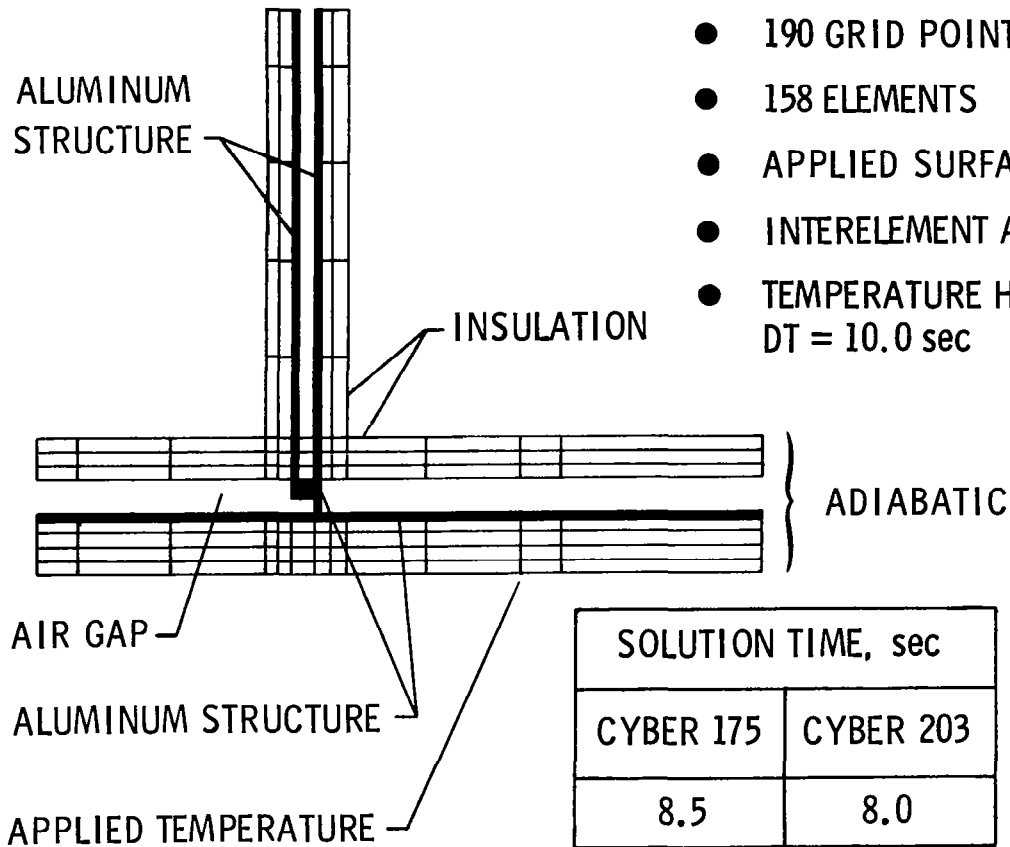
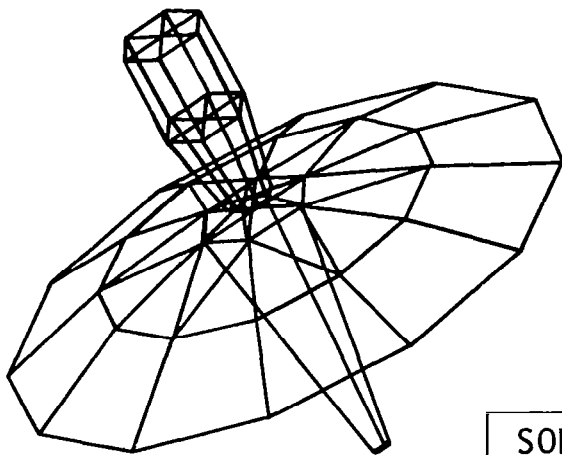


Figure 5

### 30 METER PRECISION DEPLOYABLE ANTENNA

A model of a 30 meter precision deployable antenna which has 55 grid points and 183 elements is shown in figure 6. Thermal loading is solar irradiation with time-dependent shadowing. Heat transfer includes conduction, inter-element radiation and radiation to space. Implicit solution times are shown at the bottom of the figure for a temperature history of 24 hours (one orbit) with a DT of 0.01 hour. The ANTENNA problem CPU time breakdown is shown in figure 4. While this problem is relatively small, the larger amount of effort in TRTB compared to the other processors results in significantly faster operation on the CYBER 203.



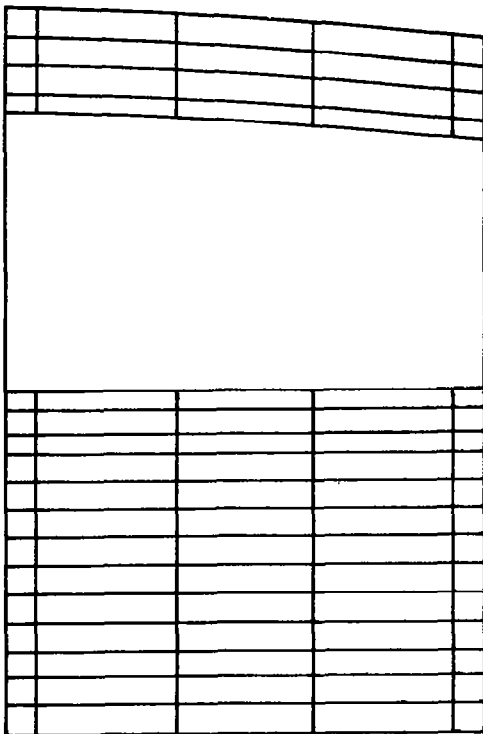
- 55 GRID POINTS
- 183 ELEMENTS
- INTERELEMENT RADIATION
- TIME-DEPENDENT SHADOWING
- TEMPERATURE HISTORY FOR 24 HOURS  
DT = .01 hr

SOLUTION TIME, sec	
CYBER 175	CYBER 203
46.4	32.1

Figure 6

## SINGLE BAY OF SHUTTLE ORBITER WING

A finite element model of a single bay of the space shuttle orbiter wing which has 123 grid points and 151 thermal elements is shown in figure 7. Thermal loading is applied as time-dependent heating on the lower and upper surfaces. Heat transfer is by conduction, internal interelement radiation and surface radiation to space. Implicit solution times for a temperature history of 2500 seconds and a DT of 1.0 sec are shown at the bottom of the figure. The SINGLE BAY problem CPU time breakdown is shown in figure 4. As the problem size increases the relative amount of CPU time spent in TRTB increases and so does the improvement over the CYBER 175.



- 123 GRID POINTS
- 151 ELEMENTS
- TIME DEPENDENT SURFACE HEATING
- INTERELEMENT AND SPACE RADIATION
- TEMPERATURE HISTORY FOR 2500 sec  
DT = 1.0 sec

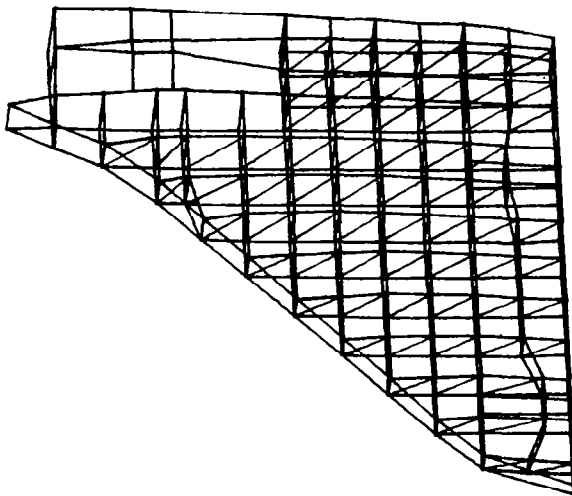
SOLUTION TIME, sec	
CYBER 175	CYBER 203
88.2	57.9

Figure 7



## SPACE SHUTTLE ORBITER WING

A thermal finite element model of the space-shuttle-orbiter primary-wing structure is shown in figure 8 (Ref. 4). The total model including the thermal protection system (TPS) which is not shown has 1542 grid points and 2125 thermal elements. This is a relatively crude model of the wing without the elevons and glove. One dimensional elements were used to model the TPS since solid elements would be much larger in the dimensions parallel to the wing surface than normal to the surface and lateral conduction is much smaller than conduction normal to the surface. Thermal loading is applied as time-dependent surface temperatures. Heat transfer is internal conduction and radiation to space. Implicit solution times for a temperature history of 3000 seconds with a DT of 100 sec are shown at the bottom of the figure. The WING problem CPU time breakdown is shown in figure 4. The larger problem size and the use of the the large number of one dimensional elements for the TPS produces the improved computational efficiency in TRTB such that the CYBER 203 uses approximately half the time of the CYBER 175.



- 1542 GRID POINTS
- 2125 ELEMENTS
- APPLIED SURFACE TEMPERATURES  
(AERO HEATING)
- 1-D ELEMENTS USED FOR RSI
- TEMPERATURE HISTORY FOR 3000 sec  
DT = 100.0 sec

SOLUTION TIME, sec	
CYBER 175	CYBER 203
144.6	85.8

Figure 8

## CYLINDER

The outer surface of a thermal finite element model of an insulated cylinder developed for solution algorithm testing is shown in figure 9 (Ref. 4). The model has 800 grid points and 650 thermal elements. Thermal loading is applied as time-dependent surface heating. Heat transfer is conduction in the aluminum shell and TPS with radiation to space from the external surface. Implicit solution times for a DT of 10 seconds are shown at the bottom of the figure. The CYLINDER problem CPU time breakdown is shown in figure 4. In this problem, the CYBER 203 takes about 40 percent as much time as the CYBER 175 for the TRTB processor.

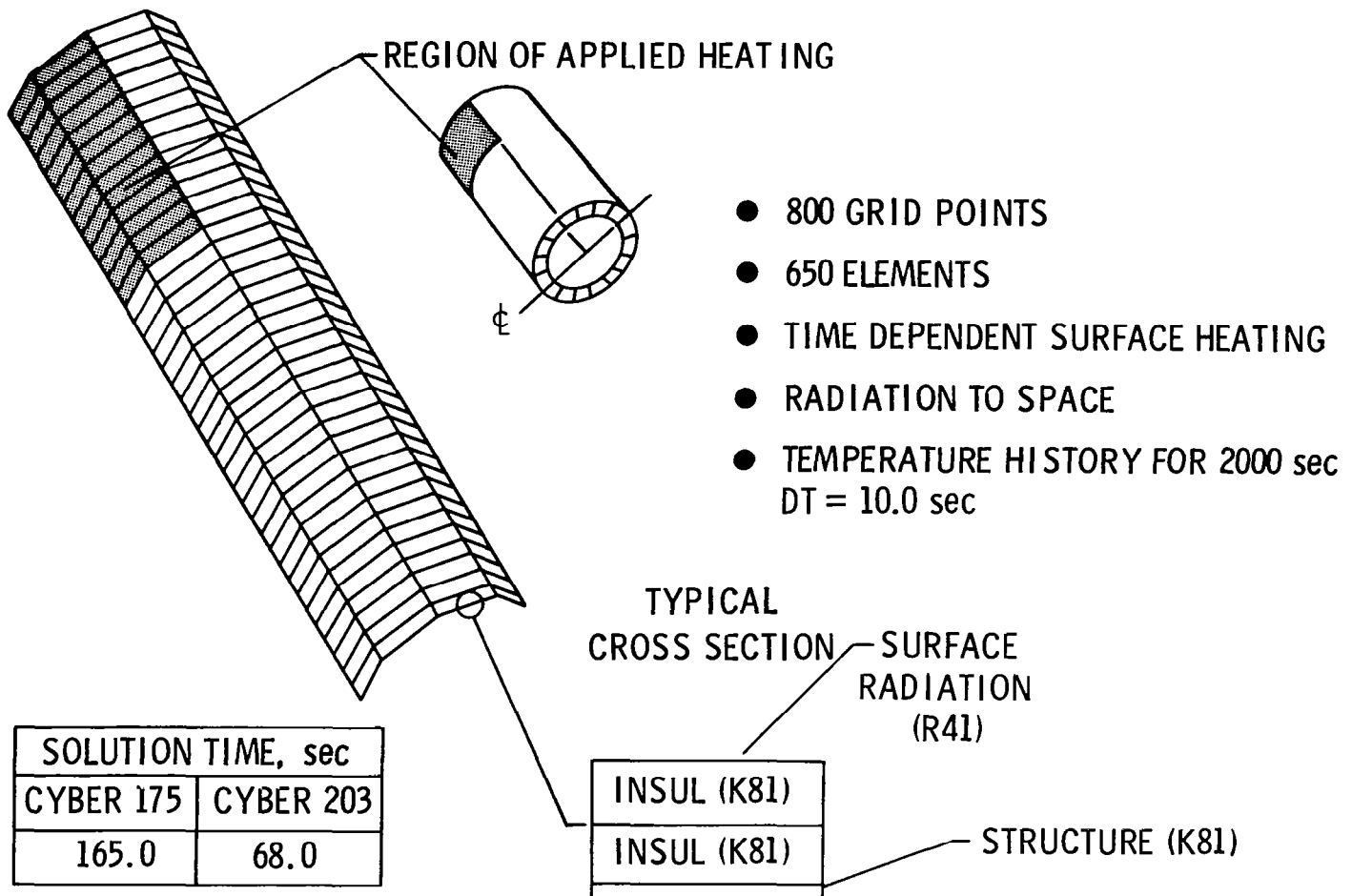
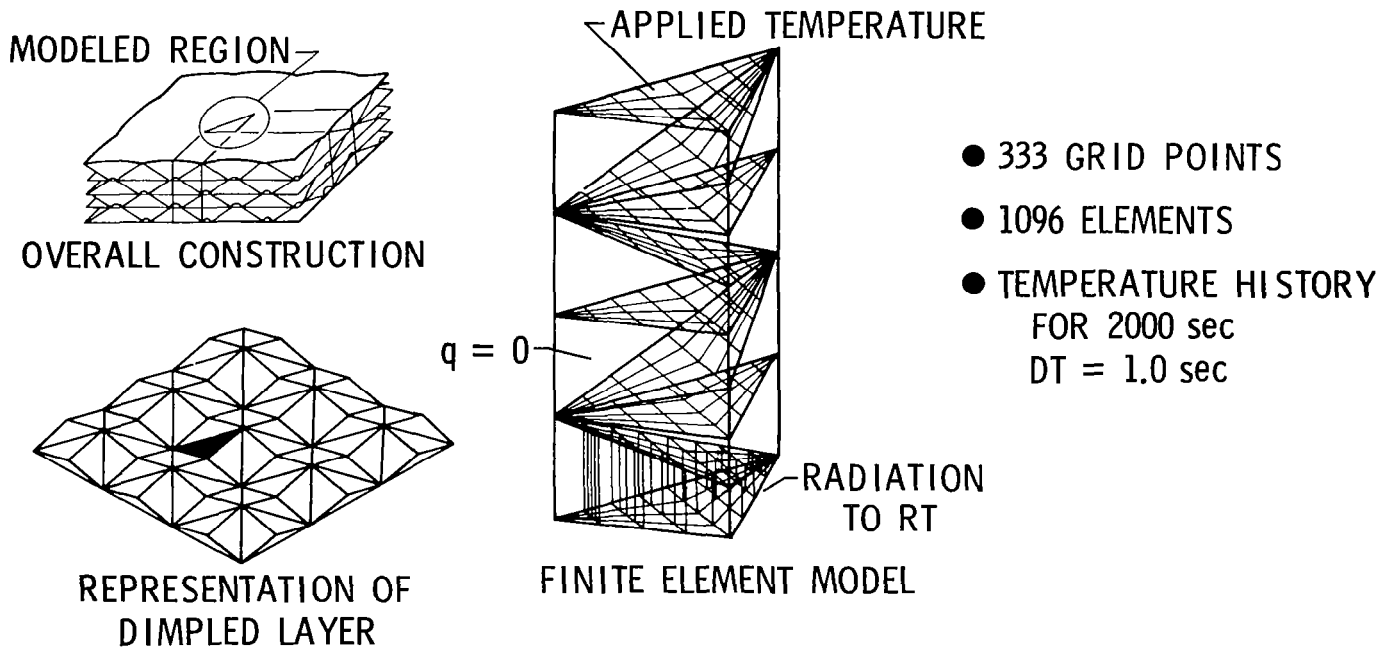


Figure 9

## MULTIWALL THERMAL PROTECTION SYSTEM

Several details and the finite element model of a piece of a multiwall thermal protection system (TPS) are shown in figure 10 (Ref. 4). As shown in the upper left sketch, multiwall TPS is made up of alternating flat and dimpled sheets of thin metal welded together at the crests of the dimples. An idealized shape for one of the dimpled sheets is shown in the lower left sketch. The finite element model has 333 grid points and 1096 elements. The thermal loading is a time-dependent temperature on the outer (upper) surface and radiation to a room temperature sink on the lower surface. Heat transfer consists of conduction in the metal sheets, radiation between the sheets and conduction in the air. Solid elements were used to model the heat transfer by conduction in the air between all the sheets but are shown between the lower two sheets only for clarity. Implicit solution times for a temperature history of 2000 seconds and a DT of 1 second are shown at the bottom of the figure. The MULTIWALL problem CPU time breakdown is shown in figure 4. The TRTB time on the CYBER 203 is about 55% of that on the CYBER 175. The increase in the AUS time is due to the input of some 37,000 terms necessary to describe radiation view factors.

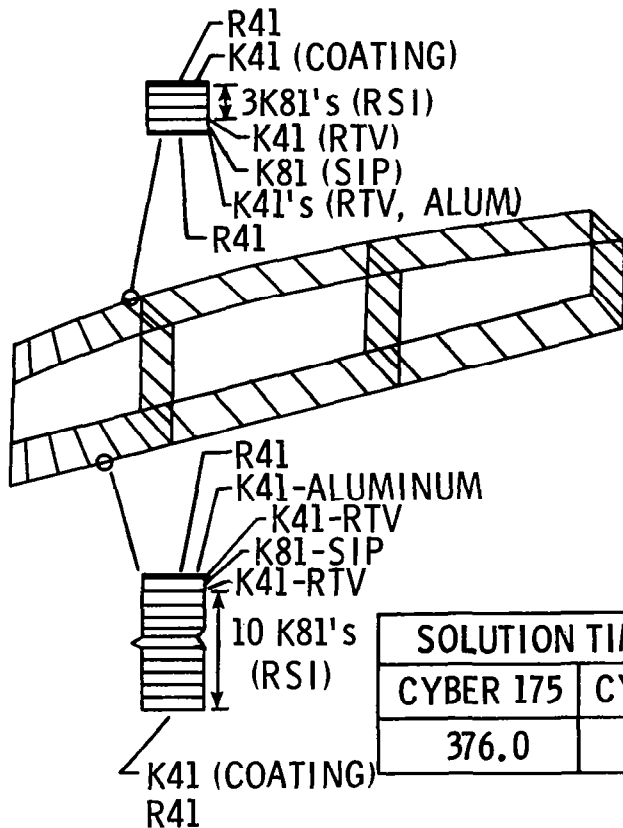


SOLUTION TIME, sec	
CYBER 175	CYBER 203
222.9	148.7

Figure 10

### THREE BAYS OF SHUTTLE ORBITER WING

A thermal finite element model of a segment of the space shuttle orbiter wing structure that extends three bays in the chordwise direction and half a bay in the spanwise direction is shown in figure 11 (Ref. 5). Modeling of the upper and lower surface thermal protection systems is shown in the details. The model has 916 grid points and 789 thermal elements. Thermal loading is time-dependent surface heating on both the upper and lower surfaces. Heat transfer consists of conduction in the metal structure and thermal protection system, interelement radiation internally and radiation to space from the outer surfaces. Implicit solution times for a temperature history of 1000 seconds and a DT of 5 seconds are shown at the bottom of the figure. The THREE BAYS problem CPU time breakdown is shown in figure 4. The TRTB time is about half as much on the CYBER 203 as on the CYBER 175.



- 916 GRID POINTS
- 789 ELEMENTS
- TIME DEPENDENT SURFACE HEATING
- INTERELEMENT AND SPACE RADIATION
- TEMPERATURE HISTORY FOR 1000 sec  
DT = 5.0 sec

Figure 11

## SPAR VECTOR STATISTICS

As stated previously, the CYBER 203 version of SPAR is basically a scalar conversion with some simple vectorization in six small subroutines that may be executed at the user's option. The six subroutines perform operations such as summing vectors and multiplying small matrices. When the seven sample problems, for which scalar results are presented in figure 4, are executed in the optional vector mode, only three of the subroutines are used and there was no decrease in solution time.

To determine why no benefits were achieved in the vector mode, data were collected on the number of times the subroutines were called and the vector lengths involved. The scalar product subroutine was called the most and performs the largest number of operations per call. The vector statistics for the scalar product subroutine are shown in figure 12. This subroutine is used within the inner loops of the implicit method as shown by the number of calls. The column displaying vector calls indicates that vector operations are not always applicable. This is typically the case when the vectors are not stored in contiguous locations. No benefit is received from the vector mode since the vector lengths, on the average, are so small. Redesign is necessary for any significant improvement to be realized.

- 6 SUBROUTINES VECTORIZED
- 3 CALLED IN THE TEST PROBLEMS
- SCALAR PRODUCT SUBROUTINE IS CALLED THE MOST AND PERFORMS MOST OPERATIONS PER CALL

RESULTS FOR SCALAR PRODUCT					
PROBLEM	NUMBER OF CALLS	NUMBER OF VECTOR CALLS	MIN. VECTOR LENGTH	AVG. VECTOR LENGTH	MAX. VECTOR LENGTH
FRAME	80,275	66,750	1	9	19
ANTENNA	264,967	245,678	1	13	34
SINGLE BAY	768,700	745,662	1	10	105
WING	896,671	693,633	1	13	259
CYLINDER	1,107,200	1,074,794	1	15	25
MULTIWALL	1,641,840	1,588,820	1	40	116
THREE BAYS	3,208,468	3,140,957	1	34	97

Figure 12

## CRANKB

CRANKB, a pilot computer program for thermal analysis of an insulated cylinder, is currently being used as a test bed for vectorization techniques. Experience gained from this pilot program will be used in determining if it is worthwhile to vectorize SPAR's thermal analyzer and possible techniques for implementation. The major reason for the selection of CRANKB is that the program, which is both small in size and simple in comparison to SPAR, already exists and has been tested. In addition, since the source code originally came from SPAR, most of the vectorization techniques used can be directly applied to SPAR. CRANKB is designed to model K81 elements and uses an implicit solution technique called CRANK-NICHOLSON. An iterative improvement method is employed in which the conductivity matrix is only updated when the solution does not converge in three iterations. A continuing effort is being applied to CRANKB. The results to date are shown on the following pages.

- TEST BED FOR VECTORIZATION TECHNIQUE
- CODE BASED ON SPAR
- PROGRAM USES K81 ELEMENTS TO MODEL INSULATED CYLINDER
- SOLUTION TECHNIQUE IS CRANK-NICHOLSON (IMPLICIT)
- STUDY NOT COMPLETE

Figure 13

## IDENTIFICATION OF TIME CONSUMING OPERATIONS

Two major time consuming operations were identified with the use of a timing utility available on the CYBER 203 (fig. 14). The major time consumer is the multiplication of the conductivity matrix by the temperature vector used in the computation of the temperature derivative. This accounts for 36% of the CPU time. The other major contributor is the factoring and solution subroutines for a symmetric banded system of equations (method  $LDL^T$ ) which accounts for 40% of the total CPU time. Together, these two operations account for 76% of the CPU time.

OPERATION	PCT OF CPU TIME
SOLUTION OF SYMMETRIC BANDED SYSTEM OF EQUATIONS (METHOD = $LDL^T$ )	40%
$[K] \{T\}$ (AT ELEMENT LEVEL)	36%

Figure 14

## IMPACT OF VECTORIZATION ON SOLUTION TIME

Figure 15 shows the vectorization stages that have been completed. The CYBER 203 run time for CRANKB before any modifications is shown in the first line of the table. The next entry displays the benefits from obvious conversions of do loops to explicit vector calls and the vectorization of scaling the element conductivity matrices.

The subroutines which factor and solve the symmetric banded system of equations were replaced by a vectorized subroutine from the CYBER 203 system math library. The answers produced were identical, and the time required for this operation was cut by almost two thirds, saving 20 CPU seconds. The library routine uses a vector length of half the bandwidth plus one. For the insulated cylinder, this turns out to be 26. A larger bandwidth would obviously produce more savings here.

The single most time consuming operation is the multiplication of the conductivity matrix, hereafter referred to as  $K$ , by the temperature vector, denoted by  $T$ . The original source does this operation at the element level which offers several advantages. The code has already been designed to store the symmetric part of the element  $K$  matrices. These are scaled for each change in temperature and then the full element  $K$  matrix is built. The corresponding temperature vector is extracted and the multiplication occurs. This is repeated for each element and the results are assembled into the global product. With this method, the global  $K$  matrix need not be built. This is advantageous since the assembly is time consuming. The major disadvantage for a vector machine is that multiplication at the element level yields small vector lengths. In the present application, the cylinder is modelled with 81 elements which produce an element  $K$  matrix of size  $8 \times 8$ .

An alternative is to do this multiplication at the system level. For the cylinder the global  $K$  matrix is  $800 \times 800$ , which appears ideal for a vector machine. The only problem is that the global  $K$  matrix must be reassembled for each multiplication. A single assembly requires 0.06 CPU seconds. For a temperature history of 1000 seconds and a  $\Delta T$  of 2.0 seconds, 627 assemblies are required taking a total CPU time of 38 seconds. Even assuming that with vector lengths of 800, the actual multiplication is negligible, no real benefit is found over the element level which takes 33 seconds.

Other less obvious alternatives were found and the actual vectorization applied is described in the next figure.



## IMPACT OF VECTORIZATION ON SOLUTION TIME

PROBLEM: 1000 sec TEMPERATURE HISTORY OF 800 NODE CYLINDER,  
DT = 2.0 sec

LEVEL OF VECTORIZATION	CPU TIME
ORIGINAL - NO VECTORIZATION	92 *
EXPLICIT VECTOR CALLS FOR OBVIOUS LOOPS AND SCALING	85
VECTORIZED ROUTINE FOR SOLUTION OF EQUATIONS (MATH LIBRARY ROUTINE)	65
VECTORIZED [K] {T} OPERATION	33

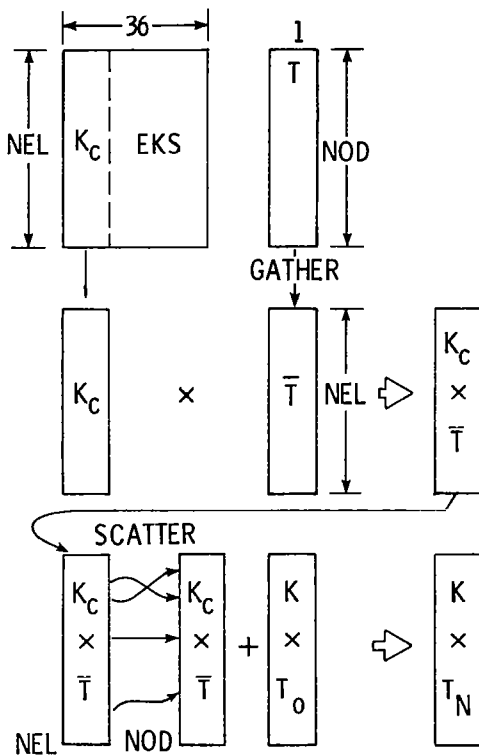
\* SPAR TIME FOR SAME PROBLEM (159)

Figure 15

## VECTORIZATION OF $[K] \{T\}$ OPERATION

The actual vectorization applied is shown in figure 16. It is by no means obvious how this sequence of operations can save time. The available storage includes an EKS matrix, dimensioned NEL by 36 where NEL is the number of elements, which contains the symmetric part of the element K matrices; an index matrix denoted by NODES (not shown) and dimensioned NEL by 8 which stores the 8 node numbers corresponding to each element; and a vector T, dimensioned NOD where NOD is the number of nodes, that contains the temperature at each node. Available on the CYBER 203 are two very efficient functions for gathering and scattering vectors. Both functions require two input vectors; a vector of real numbers representing the values to be used in the operation and a vector of integer numbers which are the array indices of the real terms. For gathering, the index vector determines which elements of the input vector are to be placed in the resultant vector. For scattering, the index vector determines where each element of the input vector is to be placed in the result.

Using the above information, with the assistance of the Langley CYBER 203 consulting office, the vectorization was implemented in the following manner. The temperature for the first node of all the elements is extracted from T using the gather function. The resulting vector (size NEL) is multiplied by the appropriate columns of EKS. Each product vector (size NEL) is scattered into another vector (size NOD) which is then added into the final result. The above is repeated for the extracted temperature vector at each of the 8 nodes. Since the gathers and scatters are efficient operations and the vector lengths are NEL, which for the cylinder application is 650, the run time is greatly reduced. The total CPU time with the vectorized  $[K] \{T\}$  operation is 33 seconds.



- T (NOD) - TEMPERATURE VECTOR
- EKS (NEL, 36) - DIAG + LOWER PART OF ELEMENT K MATRIX
- LONGEST COLUMNS, NO ZEROES
- "GATHER" TERMS FROM T TO FORM MODIFIED TEMP VECTOR,  $\bar{T}$
- DO TERM BY TERM MULTIPLY OF EKS COLUMN ( $K_C$ ) BY  $\bar{T} \Rightarrow K_C \bar{T}$
- "SCATTER" TERMS FROM  $K_C \bar{T}$  (NEL) TO  $K_C \bar{T}$  (NOD)
- ADD COLUMN PRODUCT TO KT VECTOR
- 36 COLUMNS + 28 COLUMNS FOR SYMMETRIC TERMS

Figure 16

## SUMMARY OF CYBER 203 EFFORT

SPAR executes successfully on the CYBER 203 in the scalar mode. A decrease in the scalar mode computation time is realized in the transient thermal analysis processor where most of the CPU time is used. Minimal vectorization was applied with no benefit due to insufficient vector lengths.

Considerable effort was applied to the pilot program CRANKB. The CPU time has been decreased by almost two thirds. The study, although not complete, shows a trade-off between programming effort and time savings for more efficient vectorization of the SPAR Thermal Analyzer for operation on the CYBER 203. (See fig. 17.)

### SPAR

- PROGRAM RUNS IN SCALAR MODE  
FOR CALCULATIONS HAVING HIGH CPU/IO  
SEE SCALAR SPEED ADVANTAGE
- INSUFFICIENT VECTORIZATION TO SHOW ANY ADVANTAGE  
6 ROUTINES VECTORIZED  
AVERAGE VECTOR LENGTH TOO SHORT IN TEST PROBLEMS

### PILOT PROGRAM

- CONSIDERABLE VECTORIZATION ACCOMPLISHED
- SHOWS SIGNIFICANT ADVANTAGE (3-D ELEMENT)
- STUDY NOT COMPLETED

### SPAR VECTORIZATION

- TRADE-OFF BETWEEN PROGRAMMING EFFORT AND BENEFITS  
NOT COMPLETE

Figure 17

## REFERENCES

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